



**HAL**  
open science

## Evolution of near-surface ramp-flat-ramp normal faults and implication during intramontane basin formation in the eastern Betic Cordillera (the Huerca-Overa Basin, SE Spain)

Antonio Pedrera, Jesus Galindo-Zaldivar, Francisco Lamas, Ana Ruiz-Constan

► **To cite this version:**

Antonio Pedrera, Jesus Galindo-Zaldivar, Francisco Lamas, Ana Ruiz-Constan. Evolution of near-surface ramp-flat-ramp normal faults and implication during intramontane basin formation in the eastern Betic Cordillera (the Huerca-Overa Basin, SE Spain). *Tectonics*, 2012, 31, pp.TC4024. 10.1029/2012TC003130 . hal-00750352

**HAL Id: hal-00750352**

**<https://hal.science/hal-00750352>**

Submitted on 11 May 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Evolution of near-surface ramp-flat-ramp normal faults and implication during intramontane basin formation in the eastern Betic Cordillera (the Huércal-Overa Basin, SE Spain)

Antonio Pedrera,<sup>1</sup> Jesús Galindo-Zaldívar,<sup>2,3</sup> Francisco Lamas,<sup>4</sup> and Ana Ruiz-Constán<sup>5</sup>

Received 30 March 2012; revised 13 June 2012; accepted 27 June 2012; published 23 August 2012.

[1] The nucleation, propagation, and associated folding of ramp-flat-ramp normal faults were analyzed from field examples developed in a brittle/ductile multilayer sequence of the Huércal-Overa Basin (SE Spain). Gently dipping sandy silt layers, which display a low cohesive strength ( $C_0 = 7$  kPa,  $\mu = 34^\circ$ ), favor the development of extensional detachments. A tectonic origin instead of a possible gravitational origin is supported by the perpendicularity between the paleoslope direction of the fluvial-deltaic environment inferred from imbricated pebbles, and the senses of movement deduced from fault slickenlines. The link between high-angle normal faults (HANFs)—formed at different levels in the layered sequence—with horizontal fault segments comes to develop ramp-flat-ramp normal faults with associated roll-over in the hanging wall. Observed extensional duplexes are formed by parallel detachments connected through synthetic Riedel faults. These Riedel faults would produce the back-rotation of the individual blocks (horses), i.e., extensional folding of the originally subhorizontal layers. There is no correlation between the analyzed ramp-flat-ramp normal faults, accommodating south-southeastward extension during Serravallian-lower Tortonian, and either the regional Alpujarride/ Nevado-Filabride west-directed extensional shear zone or the top-to-the-north detachments within Alpujarride units, which are clearly sealed by Serravallian-lower Tortonian sediments. Therefore, the studied normal faults are restricted to the brittle/ductile multilayer fluvio/deltaic sequence and accommodate moderate late extension instead of belonging to a large crustal extensional system connected with a regional detachment at depth. Therefore, the basin formed in a moderate crustal thickness context where small and medium-scale extensional systems were subordinate structures. These natural examples support the development of low-angle normal faults at very shallow crustal levels in multilayer sequences with suitable rheological conditions.

**Citation:** Pedrera, A., J. Galindo-Zaldívar, F. Lamas, and A. Ruiz-Constán (2012), Evolution of near-surface ramp-flat-ramp normal faults and implication during intramontane basin formation in the eastern Betic Cordillera (the Huércal-Overa Basin, SE Spain), *Tectonics*, 31, TC4024, doi:10.1029/2012TC003130.

## 1. Introduction

[2] Mechanical models of brittle faulting suggest that normal faults deforming isotropic rocks under vertical and

horizontal orientations of principal stresses, and with coaxial strain history, are developed at high-angle dips, close to  $60^\circ$  [Anderson, 1951]. However, normal faults frequently show complex arrays of interaction that link high-angle and low-angle segments in nature [Peacock and Sanderson, 1992; Morley, 1999]. Deflected stresses [Axen, 1992] and low friction linked to high fluid pressure [Axen, 1992; Collettini and Barchi, 2002, Collettini et al., 2006] and/or mineralogical weakening [Abers, 2009; Boulton et al., 2009; Smith and Faulkner, 2010] have been invoked to explain the mechanics of these low-angle normal faults (LANFs). Accordingly, extension in the upper crust is commonly accommodated by listric faults [Bally et al., 1981; Shelton, 1984] and/or planar domino style faults [Axen, 1988] rooted into a detachment at depth. In some extensional terrains, regional LANFs accommodate large displacements at middle to lower crustal levels [Lister and Davis, 1989; Axen, 1999; Cichanski, 2000; Sorel, 2000].

<sup>1</sup>Instituto Geológico y Minero de España, Granada, Spain.

<sup>2</sup>Departamento de Geodinámica, Universidad de Granada, Granada, Spain.

<sup>3</sup>Instituto Andaluz de Ciencias de la Tierra, CSIC–Universidad de Granada, Granada, Spain.

<sup>4</sup>Departamento de Ingeniería Civil, Universidad de Granada, Granada, Spain.

<sup>5</sup>Géosciences Montpellier, Université Montpellier II, Montpellier, France.

Corresponding author: A. Pedrera, Instituto Geológico y Minero de España, C/Alcázar del Genil 4, E-18006 Granada, Spain. (pedrera@ugr.es)

[3] The aim of this contribution is to analyze the geometry and the evolution of near-surface ramp-flat-ramp normal faults and associated extensional duplexes. To do so, we analyzed meso-scale examples that deform a Serravallian-lower Tortonian brittle/ductile multilayer sequence of the Huércal-Overa Basin (SE Spain) using structural data and structural modeling. This field-based characterization of the selected structures allows us to analyze their evolution, including fault initiation, linkage between high-angle and low-angle dipping normal faults, propagation mechanisms, and associated folding styles. The Betic Cordillera is as a good laboratory to explore extensional systems and the great variety of related problems. Therefore, mechanical analyses carried out in metamorphic rocks affected by large detachments mainly during early Miocene have been previously performed [e.g., *García-Dueñas and Martínez-Martínez, 1988; Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989; García-Dueñas et al., 1992; Martínez-Martínez and Azañón, 1997; Martínez-Martínez et al., 2002*]. Our results shed light on the continuity of these large extensional systems that affected metamorphic complexes of the Eastern Betic Internal Zones up to the Serravallian-early Tortonian, and their relationship with the intramontane basin formation.

## 2. Geological Setting

[4] The Betic Cordillera, together with the Rif, constitutes the westernmost part of the Alpine Mediterranean belt in the convergent Eurasian and African plate boundary [*Dewey et al., 1989; Mazzoli and Helman, 1994; Rosenbaum et al., 2002*]. Three main geological domains are recognized in the Betic Cordillera: the External Zones formed by Mesozoic and Cenozoic sedimentary rocks, the Flysch Units composed of Cretaceous to Miocene deep-water detrital sediments, and the Internal Zones composed of stacked allochthonous tectonic nappes that extensively include Paleozoic and Mesozoic rocks mostly metamorphosed in alpine times. Thrust-and-fold successions deformed the External Zones and the Flysch Units during the latest Oligocene-early to middle Miocene, associated with a westward drift of the Internal Zones [*Balanyá and García-Dueñas, 1987; Crespo-Blanc and Campos, 2001; Luján et al., 2003*]. Three main tectonic complexes constituting the Internal Zones have recorded an intense deformation history. From bottom to top they are: the Nevado-Filabride, the Alpujarride and the Malaguide [*Egeler, 1963; Van Bemmelen, 1927; Blumenthal, 1927*].

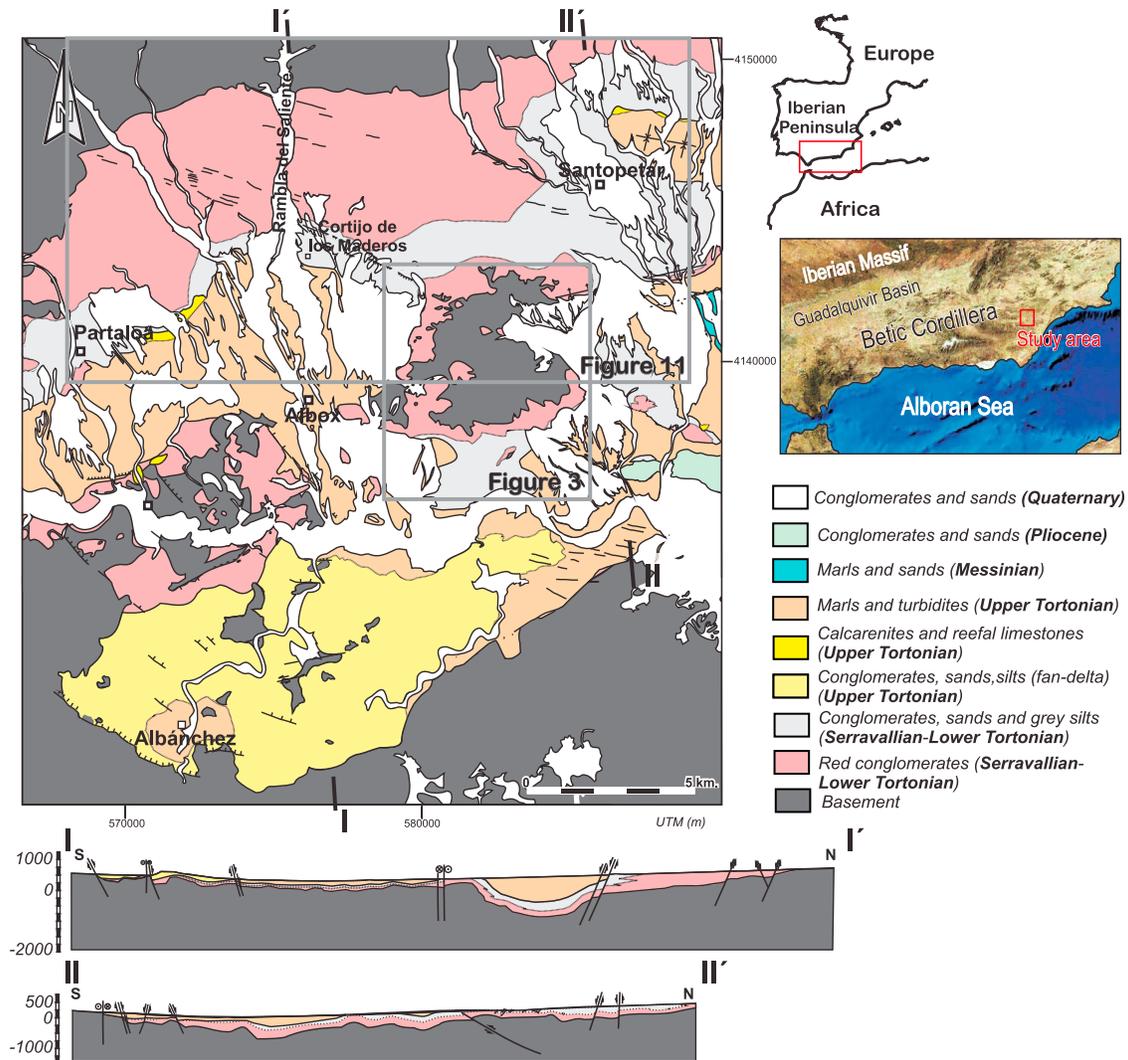
[5] The extensional opening of the Algero-Balearic Basin, related to the roll back of a northward subducting African slab, forced the westward migration of the Alboran Domain [e.g., *Booth-Rea et al., 2007*]. Accretion along the frontal sector of the Gibraltar Arc was simultaneous to a complex extension in the inner part of the Alboran Domain (Internal Zones of the Betic Cordillera) mainly during the early Miocene [e.g., *García-Dueñas et al., 1992; Jabaloy et al., 1992*]. The subduction of oceanic crust and the Iberian margin beneath the Alboran Domain and the subsequent slab roll-back, reasonably explain the latest Oligocene to middle Miocene evolution of the Betic-Rif cordilleras and the development of the Alborán Basin [*Lonergan and White, 1997; Jolivet and Faccenna, 2000; Faccenna et al., 2004*].

### 2.1. Accretion and Metamorphism in the Betic Internal Zones

[6] In Alpine orogeny, while the uppermost Malaguide Complex is largely unmetamorphosed, the Alpujarride and the Nevado-Filabride complexes were deformed under variable metamorphic conditions. Both complexes experienced a HP/LT metamorphic event, locally reaching eclogitic metamorphic conditions (lower part of the Ojen Units in the western Betics [*Tubía and Gil Iburguchi, 1991*] metabasites from the Nevado-Filabride Complex, [*Puga et al., 1999*]). Timing of the HP/LT peak is largely discussed and almost certainly it was diachronous during the Paleogene [*Monié et al., 1991; Augier et al., 2005a; Platt et al., 2005*], although an earliest Miocene age has also been evoked [*López Sánchez-Vizcaino et al., 2001; Gómez-Pugnaire et al., 2004; Platt et al., 2006*]. The HP/LT metamorphic event was related to the nappe stacking of the metamorphic complexes in a setting of collision and crustal thickening. Transpressive stacking probably continued after decompression, reshuffling the metamorphic isogrades [*Balanyá et al., 1998*]. It resulted in late-metamorphic overturned folds and the development of north to northwestward brittle thrusts crosscutting the folds and inducing the superposition of Alpujarride tectonic units [*Simancas and Campos, 1993; Balanyá et al., 1997, 1998*]. Some authors support a single extensional collapse event after the HP/LT peak, explaining the metamorphic evolution and the development of ductile to brittle shear zones and folds in a purely extensional framework that determined the development of large LANFs [*Platt, 1998; Orozco et al., 2004; Augier et al., 2005b*].

### 2.2. Low-Angle Extensional Shear Zones, Alboran Basin Development, and Late Intramontane Basin Individualization

[7] The attenuation of the Alpujarride and the Nevado-Filabride units, favored by the activity of regional extensional detachments and associated normal faults, is broadly accepted [*Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989; García-Dueñas et al., 1992; Martínez-Martínez and Azañón, 1997*]. Hence, a large-scale extensional shear zone is located at the contact between Nevado-Filabride and Alpujarride complexes, known as the Filabres shear zone [*García-Dueñas and Martínez-Martínez, 1988; Martínez-Martínez et al., 2002; Agard et al., 2011*], Mecina Extensional System [*Galindo-Zaldívar et al., 1989; Jabaloy et al., 1992*] or Alpujarride/Nevado-Filabride extensional contact [*Jabaloy et al., 1993a*]. This regional detachment shows a progressive evolution from ductile (~22–18 Ma) to ductile-brittle (18 Ma to 14 Ma) conditions accommodating top-to-the-west extension [*Augier et al., 2005b; Agard et al., 2011*]. Secondary westward-southwestward directed normal faults are associated with the main shear zone. *Martínez-Martínez and Azañón [1997]* described listric fans coalescing in the basal Filabres detachment and extensional horses bounded by LANF segments. The development of the Filabres extensional shear zone decisively contributed to the exhumation of the Nevado-Filabride Complex. In addition, a north-northwestward normal fault system attenuated the Alpujarride units during Burdigalian-Langhian times [e.g., *Crespo-Blanc, 1995; Martínez-Martínez and Azañón, 1997; Booth-Rea et al., 2004*], partially reworking the previous thrust systems [*Cuevas et al., 1986; Simancas*



**Figure 1.** Simplified geological map, cross-sections, and stratigraphy of the Huércal-Overa-Basin, located in the eastern Betic Cordillera, southern Iberian Peninsula. The positions of Figure 3 and 11 are marked.

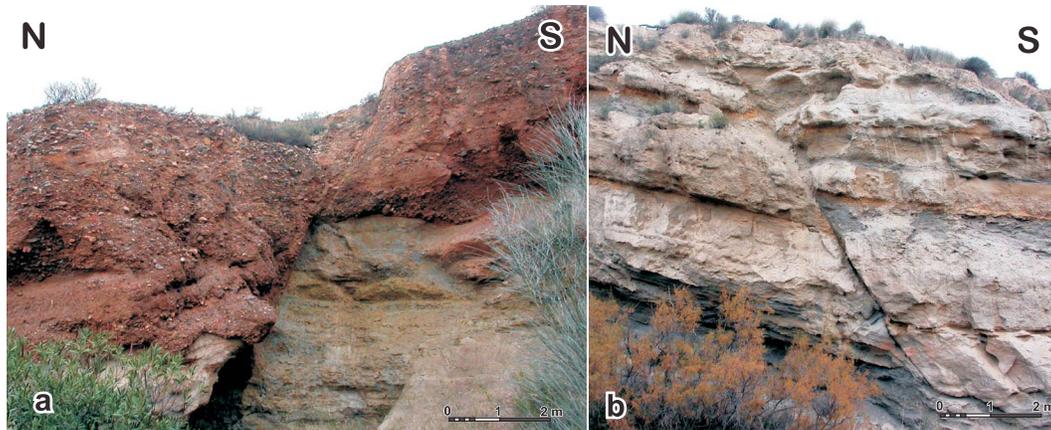
and Campos, 1993]. This normal fault system encloses listric and LANFs that coalesce into a single detachment [García-Dueñas *et al.*, 1992].

[8] The Viñuela group (early Burdigalian, ~19 Ma) [Martín-Algarra, 1987] is the first sedimentary unit containing pebbles from the Alpujarride Complex. The mechanical contact between the Malaguide and the Alpujarride complexes is locally sealed by this sedimentary unit postdating the syn-metamorphic main foliation and the exhumation of the Alpujarride units [Martín-Algarra, 1987; Jabaloy-Sánchez *et al.*, 2007]. This extensional process culminated in a significant crustal thinning in the western Alboran Basin and the deposition of Burdigalian-Langhian pelagic marls [Comas *et al.*, 1999]. From late Serravallian onward, the emersion of the northern Alboran Basin margin occurred, inducing progressive intramontane basin disconnection. This moment is marked by an angular unconformity between Burdigalian-Langhian pelagic marls, incompletely preserved, and a Serravallian-lower Tortonian continental/fluvial-deltaic sedimentary unit. The Huércal-Overa Basin,

placed in the eastern Betic Cordillera, is one of these sedimentary basins.

### 2.3. The Huércal-Overa Sedimentary Basin

[9] The Huércal-Overa Basin is located between the E-W to ENE-WSW trending Sierra de Los Filabres/Sierra de Almagro and Sierra de Las Estancias (Figure 1). According to a compilation of stratigraphical analyses [e.g., Briand, 1981; Montenat *et al.*, 1990; Mora, 1993; Augier, 2004; Meijninger, 2006; Pedrera *et al.*, 2010], the stratigraphical sequence starts with a thick continental red conglomerate formation (reaching up to ~500 m in thickness), Serravallian-early Tortonian in age, which lies unconformably on the metamorphic basement. These continental deposits are in gradual lateral and upward transition toward a fluvial-deltaic unit (reaching up to ~300 m in thickness), also Serravallian-early Tortonian in age, where brittle conglomerates alternate with sandstone levels and soft beds made up of homogenous gray sandy silts, clays, caliches, paleosols and gypsum. At the top of the Serravallian-lower Tortonian units lies an



**Figure 2.** Field examples of faults. (a) Example of WNW-ESE high-angle normal fault that deforms Serravallian-early Tortonian conglomerates. (b) WNW-ESE high-angle normal fault that decreases in dip downward, occasionally becoming parallel to the gray silt beds.

angular unconformity, and late Tortonian bioclastic limestones are found in gradual transition to yellow marls toward the center of the basin where reach up to  $\sim 800$  m in thickness. Messinian marls crop out only in the easternmost part of the basin. During the Plio-Quaternary, Miocene series were highly eroded and detrital alluvial and fluvial sediments were unconformably over the Miocene rocks.

[10] The Miocene sediments that fill in the Huércal-Overa recorded extensional and compressional deformations [Pedrera *et al.*, 2010]. It offers an opportunity to study field examples of small-scale and meso-scale normal faults [Briend, 1981; Guerra Merchán, 1992; Mora, 1993; Augier, 2004; Meijninger, 2006; Pedrera *et al.*, 2007, 2010]. Normal faults that are WNW-ESE to NW-SE oriented show a widespread distribution, with evidence of activity since the Serravallian-early Tortonian. Kinematic analysis of both HANFs and LANFs generally reveals NNE-SSW to NE-SW extension in transition to radial extension [Pedrera *et al.*, 2007, 2010]. Yet Mora [1993] and Augier [2004] support two successive and almost perpendicular extensional stress fields. Most of the normal faults develop planar surfaces dipping  $50\text{--}60^\circ$  (Figure 2). However, LANFs that developed in the fluvial-deltaic unit interact with HANFs, giving rise to extensional duplexes and ramp-flat-ramp normal faults.

#### 2.4. Contrasting Tectonic Models

[11] Several models are proposed to explain the E-W to ENE-WSW oriented ranges and adjacent intramontane sedimentary basin formation in the Betics since late Serravallian. Some authors propose that E-W elongated Sierra Nevada-Sierra de los Filabres dome, and associated ranges, have a contractional origin, which is also affected by an isostatic adjustment due to progressive unroofing at the footwall of the Filabres regional basement detachment [e.g., Martínez-Martínez *et al.*, 2002, 2004]. Augier *et al.* [2005a] propose the relief and basin genesis in a pure extensional deformation setting where the Sierra Nevada-Sierra de los Filabres metamorphic dome progressively grows through the superimposition of an E-W regional extension and a lateral downslope N-S extension induced by gravity in Serravallian-Tortonian times. This N-S extension would be

accommodated by listric normal faults rooted on the reactivated Filabres shear zone. Meijninger [2006] propose the late Serravallian to late Tortonian Basin formation in response to the approximately N to NE directed extension, also in an extending crustal setting. This N to NE oriented extension direction should induce extensional faulting both in the basins and in the underlying basement. In contrast, Pedrera *et al.* [2007, 2010] support the formation of the basins in a context of moderate crustal thickening with the coeval interplay of contractional and subordinated extensional tectonic structures. The nearby Alhama de Murcia left-lateral Fault Zone is a key major structure controlling the basin genesis [Pedrera *et al.*, 2010]. The Sierra de Los Filabres would correspond with an antiform resulting from contraction [Weijermars *et al.*, 1985; Montenat and Ott d'Estevou, 1990; Sanz de Galdeano and Vera, 1992] and nucleated in a heterogeneous upper crust favored by the presence of basic rocks [Martí *et al.*, 2009; Pedrera *et al.*, 2009].

#### 3. Methods

[12] Ramp-flat-ramp normal faults and associated extensional duplexes were analyzed from field examples developed in the Serravallian-lower Tortonian brittle/ductile multilayer sequence of the Huércal-Overa Basin. To begin, we explored their possible connection with a large basement extensional system, as previously suggested [Augier *et al.*, 2005b]. For this purpose, we characterized the detachments, separating the metamorphic complexes that constitute the basement by new geological mapping and kinematics analysis. We pay attention to the timing and kinematic relationships between the basement detachments and the ramp-flat-ramp normal faults affecting the sedimentary rocks of the Huércal-Overa Basin.

[13] Subsequently, we focus on the geometry, kinematics, fault gouge features and related fold geometry of the selected ramp-flat-ramp normal faults affecting the basin. After recognition of the folding mechanism, deformation analysis through the cross-section restoration of key examples was carried out, conserving the bed-length and cross-sectional

area and considering shear parallel to the beds, in order to understand and quantify the fault slip.

[14] Triaxial tests of selected samples from the soft beds that accommodate the deformation of flat segments were also performed to obtain the cohesive strength and the sliding friction coefficient [e.g., *Bardet, 1997; Head, 1998*]. We compare the kinematics of the normal fault surfaces developed as opposed to the paleoslope direction deduced from the pebble imbrications in order to explore the possibility of a synsedimentary gravitational origin. Finally, we propose the genetic and evolutionary model of the near-surface ramp-flat-ramp normal faults and discuss the regional implications of the work.

#### 4. Detachments in the Basement of the Huércal-Overa Basin

[15] The detachment levels that affect the Alpujarride Units outcropping in the Limaria sector, in the center of the Huércal-Overa Basin, are characterized in Figure 3. The presence of LANFs crosscutting the basal sedimentary unit of the Huércal-Overa Basin could initially suggest that basin formation resulted from large-scale extension accommodated along the crust-penetrating extensional detachment faults described in the metamorphic basement. Therefore, from a regional point of view, we explore two possible hypotheses: (a) that the studied extensional detachments, affecting the Serravallian-early Tortonian deposits of the Huércal-Overa Basin, are connected with a regional extensional basement system, being mainly controlled by an overall extensional setting; (b) that these near-surface detachments are a local and subordinated feature restricted to the Serravallian-early Tortonian fluvio-deltaic deposits accommodating a moderate extension and mainly controlled by the primary rheology of the deformed rocks.

##### 4.1. Alpujarride Units in the Limaria Sector

[16] We have mapped the tectonic structures in the Limaria Sector, which is placed in the central part of the Huércal-Overa Basin (Figures 1 and 3). The structural map shows the relationships between the mechanical contact separating metamorphic units and the late extensional systems deforming the sedimentary rocks of the basin.

[17] Isolated Paleozoic dark colored schists with garnets belonging to the Nevado-Filabride complex crop out in the southern part of the sector (Figure 3). The outcrops are unconformably covered by the Serravallian-lower Tortonian basal sedimentary unit.

[18] Most of the basement rocks cropping out in the Limaria sector belong to the Alpujarride Complex. The uppermost tectonic Alpujarride unit is the Variegato Unit, which is formed by three formations. The first, at its base, comprises Palaeozoic dark schists with garnet and biotite. Above it lies a formation of bluish-gray phyllites and quartzites. At the top there is a carbonate formation containing layered calcschists, limestones, and phyllites, evolving upward to thick dark dolomites that are probably Triassic in age. The largest preserved thickness of the whole unit is around 200 m in the Limaria hill (Figure 3b). This unit has been recognized in the northern part of Sierra de Los Filabres [*De Jong, 1991*] and in the nearby Sierra de Almagro [*Simon, 1963; Barragán, 1997; Sanz de Galdeano*

and *García-Tortosa, 2002; Booth-Rea et al., 2002, 2003, 2005*].

[19] Beneath the Variegato Unit lies the Almanzora Unit, previously recognized in Sierra de los Filabres [*De Jong, 1991*] and Sierra de Almagro [*Simon, 1963; Booth-Rea et al., 2002, 2003, 2005*] in the same tectonic position. Here it is formed by a layered sequence of chlorite-bearing fine-grained schists and phyllites, quartzites, local gypsum layers, and metabasites that give rise upwards to light calcschists and dolostones.

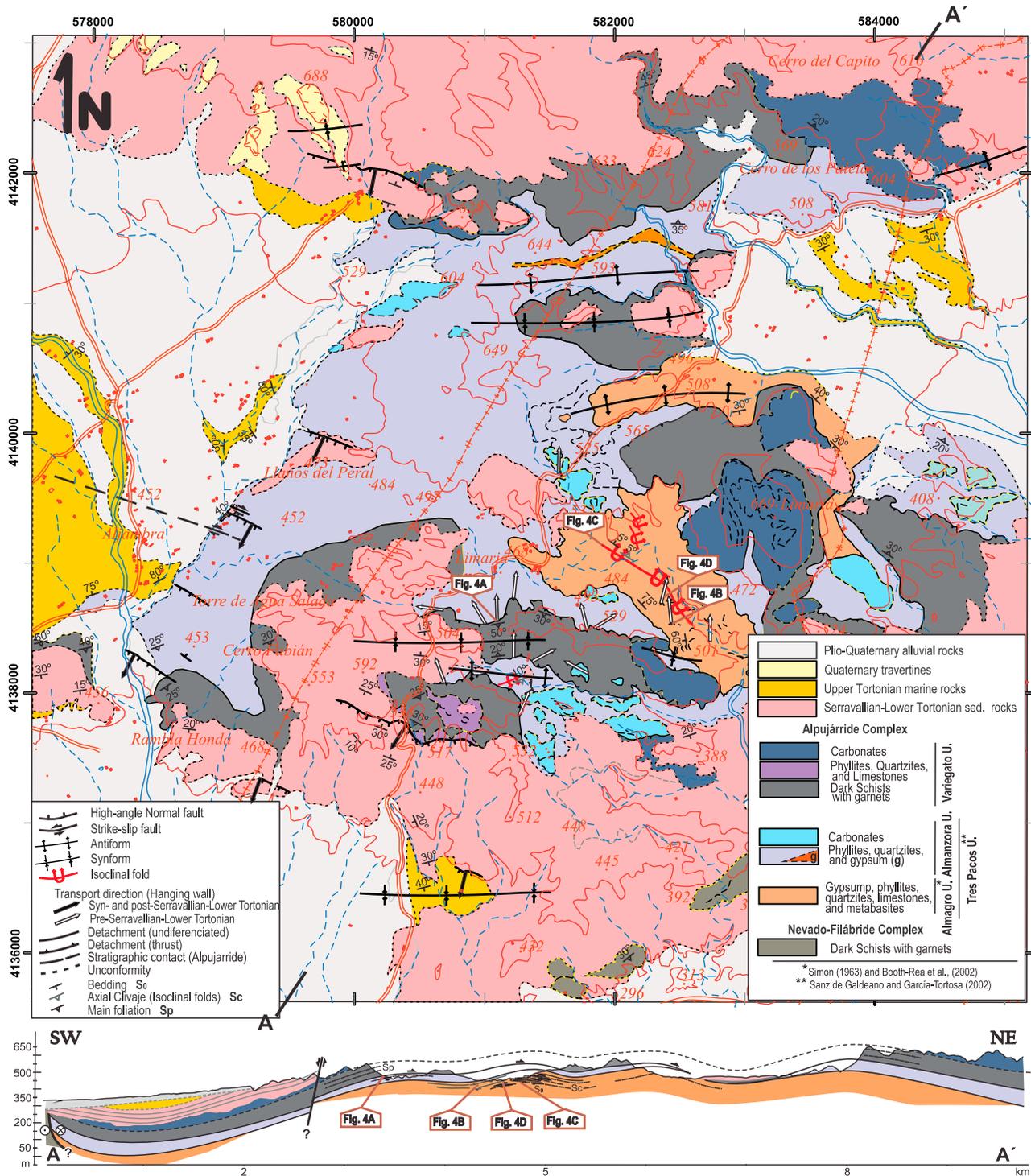
[20] The lowermost tectonic unit is formed by a sequence of alternating pelites, sandstones, carbonates, local igneous basic rocks, and abundant gypsum that, depending on the authors, belongs to the Almagro unit [*Booth-Rea et al., 2003*] or is integrated into the Almanzora units forming part of the Tres Pacos unit [*Sanz de Galdeano and García-Tortosa, 2002*]. This discrepancy remains beyond the scope of the present work: in any case, it is the lowest metamorphic outcropping sequence, reaching only lower-green schist facies [*Simon, 1963; Booth-Rea et al., 2002*].

##### 4.2. Nature and Kinematics of the Contacts

[21] We have characterized two detachment zones outcropping within the Alpujarride units of Limaria hill and explored their relationships with the widespread WNW-ESE to NW-SE normal faults that affect the sedimentary rocks of the basin.

[22] The garnet-biotite-bearing schists of the Variegato unit are tectonically placed above chlorite-bearing fine-grained schists and phyllites of the Almanzora unit (Figures 3 and 4). This tectonic contact is a predominantly low-dipping ten-meter-thick fault zone that displays slickenlines and S-C structures indicating a top-to-the-N sense of shear. This is also consistent with small-scale NE-verging overturned folds that deform the main foliation placed close to the fault zone (Figure 4a). This detachment is clearly sealed by the Serravallian-lower Tortonian sedimentary unit and is deformed by E-W late folds and the WNW-ESE high-angle normal faults (Figures 2 and 3). The presence of HP/LT metamorphic rocks above lower-pressure ones suggests that this detachment is a thrust. This probable late to post-metamorphic thrusting event was already recognized in the Sierra de Almagro [*Booth-Rea et al., 2002, 2005*].

[23] The contact between the Almanzora schists and the Almagro unit is a shear zone that broadly develops a gypsum mylonitic foliation showing a top-to-the-N sense, which is recorded by the N-S preferential orientation of the gypsum crystals and associated  $\sigma$ -type porphyroclasts (Figure 3 and 4b). This contact also crops out southward, in the southern limb of the Sierra de Almagro antiform, the so-called Almagro detachment [*Booth-Rea et al., 2005*]. There, *Booth-Rea et al.* [2005] describe a set of LANFs related with the Almagro detachment, and propose its extensional character. We observed no LANFs linked to the Almagro detachment in the Sierra Limaria. The most prominent structures there are isoclinal folds that are NE-SW to N-S oriented with associated axial plane cleavage, and are placed beneath the detachment, within the Almagro unit (Figures 3 and 4c). The activity of the Almagro detachment and the isoclinal folds was probably coeval. Close to the shear zone, folds hinge lines are highly curvilinear, locally developing sheath folds



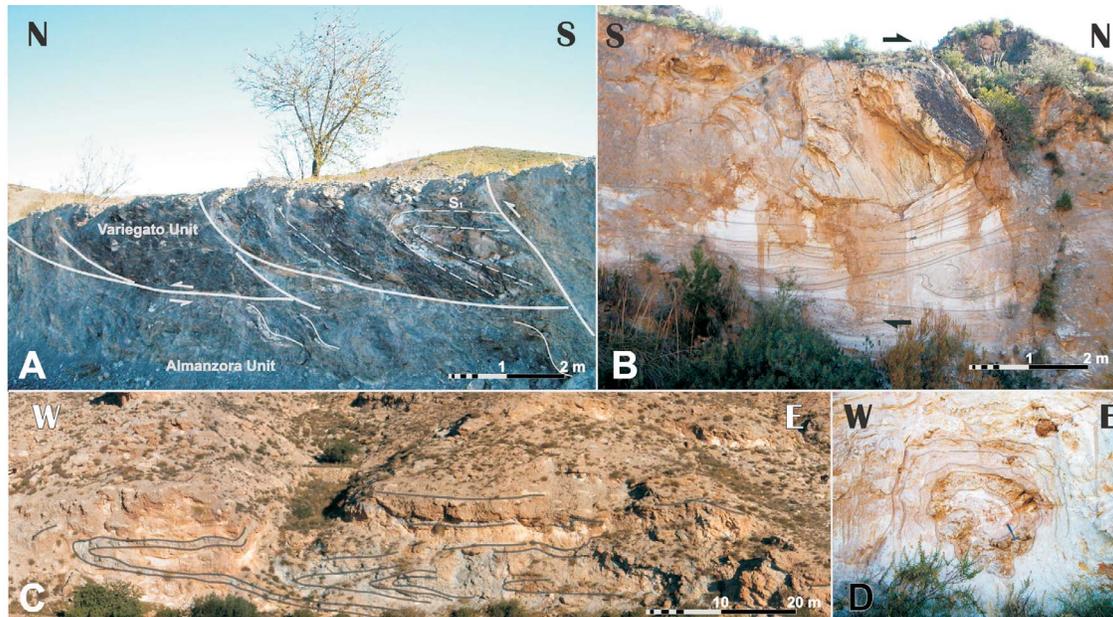
**Figure 3.** (a) Structural map of Limaria sector and (b) cross-section. The locations of the outcrops of Figure 4 are marked.

parallel to the transport direction (Figure 4d). The presence of related isoclinal folds, the fact that the higher metamorphic Alanzora unit is placed above the Almagro unit, and the coincident N-directed kinematics with the Variegato-Alanzora contact suggest that it is also a thrust. In any case, the Almagro detachment is sealed by Serravallian-early Tortonian red continental conglomerates, including clasts of

the Almagro and Alanzora units, both around the Limaria sector and around Sierra de Almagro (Figure 3).

### 5. Ramp-Flat-Ramp Normal Faults in the Huércal-Overa Basin

[24] Examples of ramp-flat-ramp normal faults are described along the Rambla del Saliente and close to



**Figure 4.** (a) Top-to the N Variegato/Almanzora thrust. (b) Gypsum mylonitic foliation and associated  $\sigma$ -type porphyroclasts showing a top-to-the- N transport direction within the Almagro detachment. (c) NE-SW isoclinal folds and associated axial plane cleavage within the Almagro unit. (d) Sheath folds within the Almagro detachment parallel to the transport direction.

Santop etar village in the northern part of the Hu ercal-Overa Basin (Figure 1). Ramp-flat-ramp normal faults are located in the fluvial-deltaic multilayered sedimentary sequence. Close to the fault ramps, the sedimentary layers are folded and form roll-overs in the hanging wall. Layers of soft homogeneous sand to sandy silt and clay layers concentrate the deformation, constituting detachment levels. Although occasional low-angle segments concentrate their slip along the discrete boundary between sedimentary layers and do not develop fault gouge, a fault gouge up to 50 cm of thickness is frequently observed. Sheared clay beds develop a fine-grained foliated fault gouge with an S-C fabric featuring small clasts floating in a silty matrix sometimes enriched in iron oxides.

### 5.1. The Santop etar Section

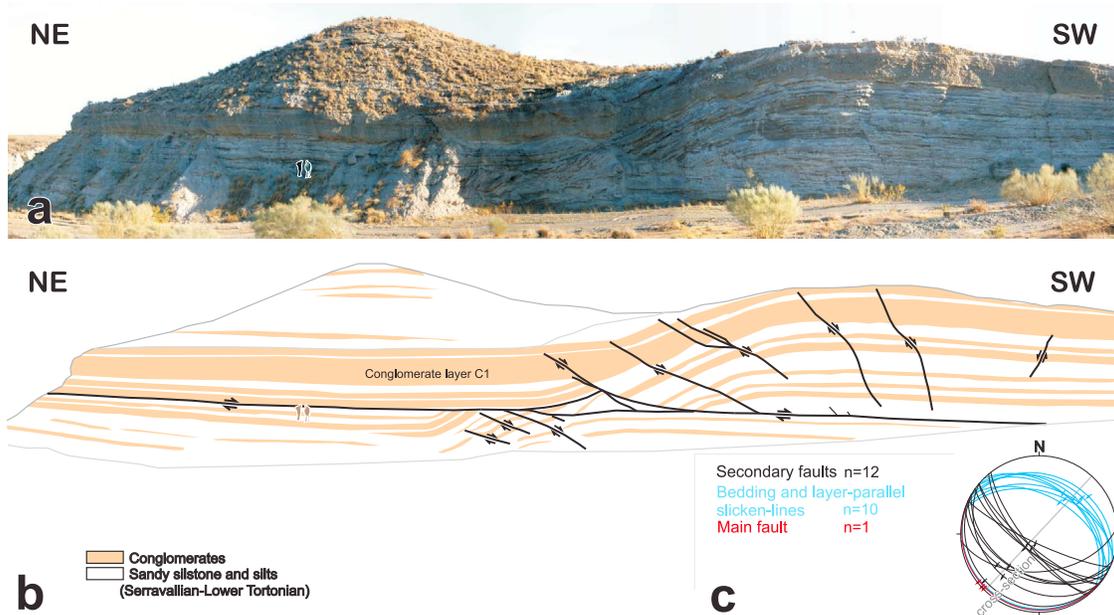
[25] The Santop etar cross-section is the best exposed outcrop of a flat fault segment with related folds (Figure 5). In the hanging wall, a N110–120 E trending gentle antiform shows an interlimb angle of  $\sim 160^\circ$ , an axial surface dipping  $\sim 85^\circ$  to the southwest, and 7 m of minimum vertical throw. Its hinge line is preserved from erosion along 60 m. In the footwall, there is a N110–120 E trending gentle synform with an interlimb angle of  $\sim 160^\circ$ , and an axial surface dipping  $\sim 80^\circ$  to the southwest, approximately symmetrical to the hanging wall antiform. The folds accommodated deformation by flexural slip along discrete silty surfaces parallel to the beds. Layer-parallel slicken-lines reveal a SW-NE direction of the tectonic transport (Figure 5). The two folds are separated by a flat fault zone that overlies a sandy silt layer accommodating southwest directed extension (Figure 5), as could be deduced from observed slicken-lines and S-C fabric. This main detachment crops out  $\sim 110$  m along the exposed section.

[26] Both folds are likewise deformed by WNW-ESE secondary normal faults with a length from 1 to 10 m that also accommodate a SW directed extension, as revealed by the presence of slicken-lines. The secondary faults strike parallel to the fold axis, and therefore parallel as well to the ramp that was related with the roll-over development. While the secondary faults located in the hanging wall of the major fault have a dip between  $65^\circ$  and  $30^\circ$  toward the SW, the secondary faults located in the footwall of the major fault have a dip lower than  $30^\circ$  toward the SW.

[27] The Santop etar structure has drawn the interest of many researchers. It was first interpreted by Briend [1981] as an example of roll-over anticline related to extensional synsedimentary deformation related to non-fully lithified sediments deformed by the load of overlying sediments. Jabaloy *et al.* [1993b] and Mora [1993] re-interpreted the structure as resulting from deformation of both the footwall and the hanging wall along a major ramp-flat-ramp normal fault system. Some years later, Augier [2004] described a “major slip zone” with a flat geometry constituted by a 2 to 20 cm thick brittle fault gouge. Most recently, Meijninger [2006] recognized several hiatuses in the hanging wall that again support synsedimentary development.

### 5.2. Extensional Shear Zones and Duplexes

[28] Examples of small and medium-scale extensional shear zones crop out along the Rambla del Saliente (Figure 1). Sub-horizontal extensional fault zones bound extensional shear lenses that are sigmoidal in shape.  $30^\circ$ -dipping Riedel faults separated lenses that contain well-cemented sands and micro-conglomerates that are back-rotated (Figure 6). They form duplex-like structures, i.e., splay faults propagate connecting overstepping straight main faults [Woodcock and Fischer, 1986].

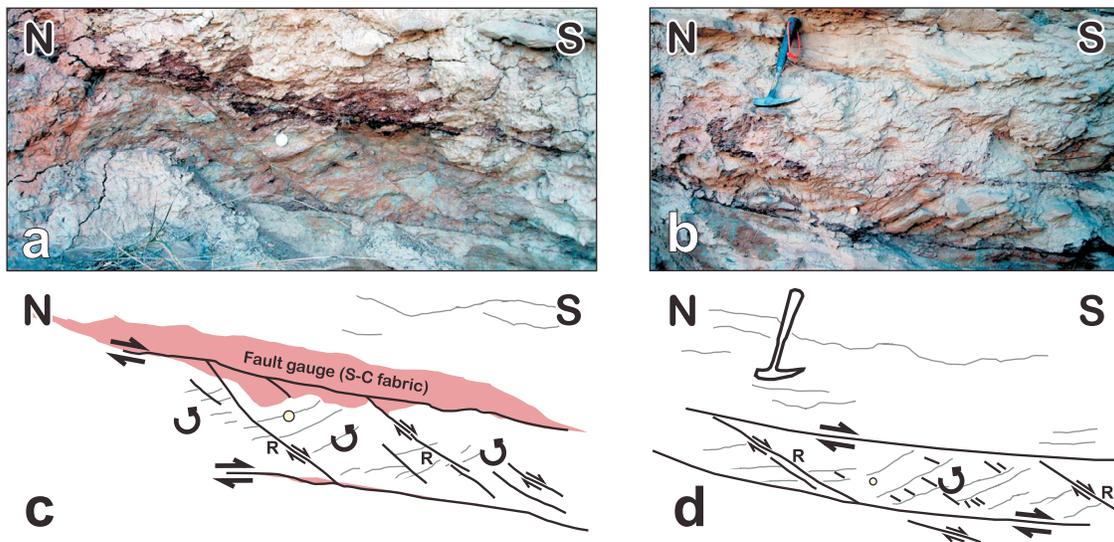


**Figure 5.** (a) Field view, (b) interpretative sketch, and (c) kinematics data of the WNW-ESE oriented Santopétar ramp-flat-ramp fault and its associated extensional folds deforming the succession of conglomerates, sands and gray silts. Note the two men as scale.

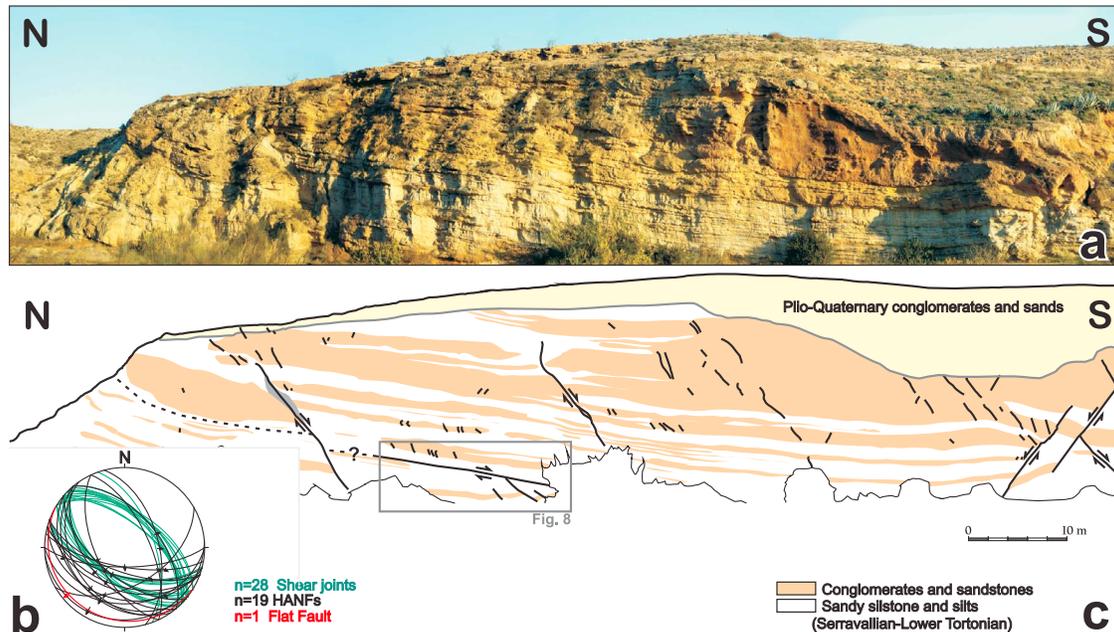
**5.2.1. The Cortijo de los Maderos Section**

[29] The Cortijo de los Maderos section is located in the southern part of the Rambla del Saliente (Figure 1). The outcrop consists of 10° south-dipping alternating conglomerates and a sandy silt sequence that are deformed by 50–70° dipping NW-SE to WNW-ESE oriented shear joints, HANFs, and LANFs (Figure 7). The conjugated NW-SE shear joints are restricted to the conglomeratic layers and spaced between 50 cm and 2 m. The HANFs that crop out

along the section trending NW-SE to WNW-ESE have conjugated planes dipping 50–60°, as well as variable length (tens to cents of meters) and offsets (decimetric to metric). At the base of the outcrop, a LANF that develops a localized footwall ramp and a hanging wall flat can be distinguished (Figure 8a). The LANF could not be identified to the north of the footwall ramp because it is completely parallel to the bedding (Figure 7), has no associated fault gouge, and is identical to the discontinuous boundaries between



**Figure 6.** (a and b) Field view and (c and d) interpretative sketch of small-scale extensional shear zones characterized by the formation of 30° south-dipping Riedel faults connected with main sub-parallel flat normal faults forming extensional duplex-like structures. Note that Riedel faults induce domains where the well-cemented sands and micro-conglomerate beds form back-rotated sigmoidal lenses. Sometimes the flat normal faults develop fine-grained foliated fault gouges.



**Figure 7.** (a) Field view, (b) kinematics data, and (c) interpretative sketch of the Cortijo de los Maderos section, formed by  $10^\circ$  south-dipping alternating conglomerates and sandy silts deformed by NW-SE to WNW-ESE shear joints, NW-SE to WNW-ESE high-angle normal faults, and low-angle normal faults. The location of Figure 8 is marked.

sedimentary beds. In the footwall, the beds are slightly curved upward, giving the general appearance of a WNW-ESE gentle synform with an interlimb angle of  $\sim 160^\circ$ ,  $\sim 55^\circ$  south dipping axial plane, and 2–3 m estimated fold amplitude. The tilted sedimentary beds are offset up to 2 m by  $30^\circ$  south-dipping WNW-ESE trending Riedel faults. As in the small-scale examples described in the previous section, the development of these Riedel fractures is responsible for the back-rotation of the beds located in the footwall of the main upper bounding detachment. The nucleation of these Riedel normal faults starts at a brittle conglomeratic level as can be seen in Figures 8a and 8b. The connection between the main flat surface and minor oblique Riedel normal faults and their coincident SW directed extension, deduced from slicken-lines and S-C fabric, would signal that both are formed during a single deformation event. The metric Riedel faults linked upwards to the master straight fault, plus the  $25^\circ$  of bedding back-rotation, suggest the existence of a linked parallel main fault downward, configuring a releasing overstep zone. The Riedel faults form a horsetail structure (i.e., an extensional duplex) that joins the outcropping upper detachment and an overstepping supposed lower one (Figure 8c).

## 6. Mechanical Analysis

[30] The mechanical behavior of three sandy silt samples collected along the Santopéтар section was characterized using an undrained triaxial test [e.g., Bardet, 1997; Head, 1998]. Samples were taken from a selected level of the Santopéтар section over a distance of 2 to 3 m (Figure 5). Cylindrical test samples protected by a rubber sleeve were analyzed, and triaxial experiments were performed under

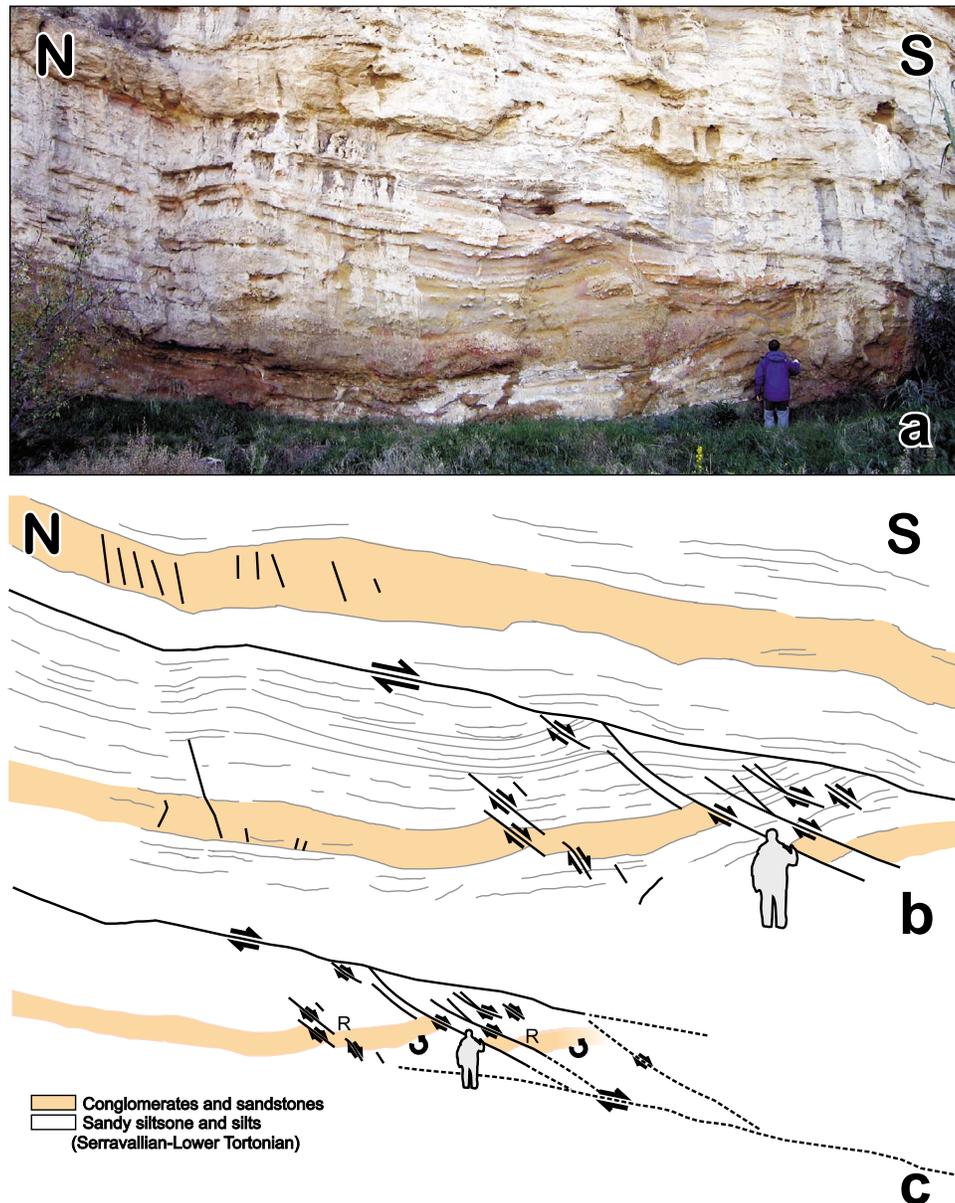
natural water conditions, at room temperature, and at constant effective normal stresses of 0.65, 0.75 and 0.9 MPa (Figure 9). The sandy silts showed a linear Mohr-Coulomb failure envelope. The obtained cohesive strength of 0.007 MPa reveals the extremely low strength between the particle surfaces that make up the sandy silts. The slope of the Mohr failure envelope gives a coefficient of internal friction of  $34^\circ$ , i.e., the ratio of the shear stress to the normal stress at failure.

## 7. Evolution and Restoration of the Santopéтар Ramp-Flat-Ramp Normal Fault

[31] The Santopéтар structure is interpreted to have developed during faulting along a ramp-flat-ramp fault surface (Figure 10). Deformation probably started within the brittle conglomerate levels with the formation of a high-angle normal fault. This precursory fault would progress up to the soft sandy silt levels where the extension was transferred parallel to the easily deformable bed. Two possible evolution models are analyzed and discussed below by using restorations that conserve bed-lengths, bed thickness and cross-sectional area.

[32] (a) Successive faulting phases model (Figure 10b). A ramp-flat-ramp normal fault developed during a top-to-the-northeast extensional phase. A bend fold formed during faulting above the northeast-dipping ramp. Later, a top-to-the-southwest flat fault partially reactivated the previous upper flat segment and offset the preceding bend fold.

[33] Figure 10b shows the restoration of the Santopéтар structure following this hypothesis. Stages 1 and 2 (Figure 10b) restore 20 m slip (point A is the deformation marker) along a major top-to-the-southwest flat fault surface that cuts and displaces the antiform-synform pair. Stages 5

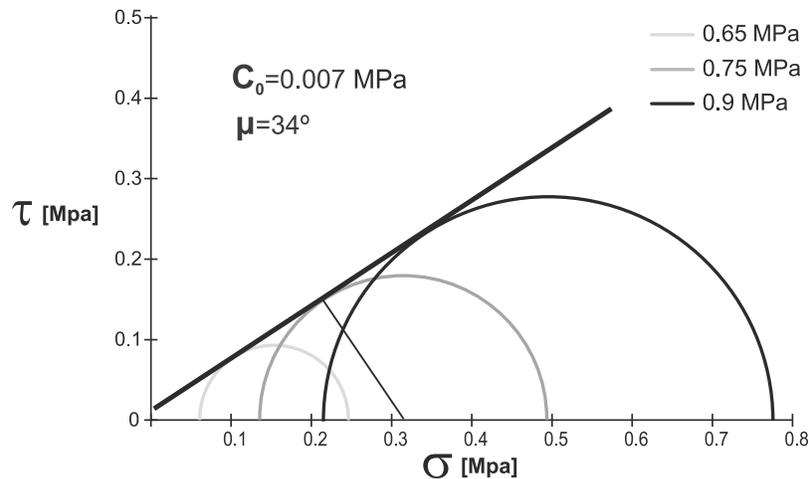


**Figure 8.** (a) Field view and (b) simplified sketch of a detachment parallel to the sandy silts beds, associated minor  $30^\circ$  south-dipping faults (Riedel faults), and a linked gentle synform observed in the Cortijo de los Maderos section. Note that Riedel faults are linked upwards to the main fault. (c) Interpretative sketch of the structure where the Riedel faults are formed in a releasing overstep zone and finally develop an extensional duplex joining the outcropping upper detachment to a supposed lower one.

and 6 reconstruct the development of the antiform-synform linked to fault-bending associated with 23 m of top-to-the-northeast ramp-flat-ramp fault activity. Stages 2, 3 and 4 show the restoration of the SW-dipping secondary normal faults. Deposition of layer C1 was underway during the activity of the adjacent SW-dipping secondary normal fault. Strata should thicken toward the fault, with maximum subsidence adjacent to the fault, while the top surface of the sedimentary layer was originally horizontal. However, at stage 4, it is impossible to restore the top surface of the C1 sedimentary layer up to the horizontal (Figure 10b, stage 4). Hence, this hypothesis is proven unsatisfactory and we discard it.

[34] (b) Single top-to-the-southwest ramp-flat-ramp normal fault model. A roll-over growth in the hanging wall is associated with block movement above a southwest dipping ramp. During the displacement of the hanging wall above the flat fault segment, a synform developed in the footwall as a consequence of the back-rotation domains bounded by SW-dipping Riedel normal faults (following the small-scale examples of parallel detachments connected by Riedel shears in Figure 6).

[35] Stages 1 and 2 of Figure 10c show the restoration of the displacements along the secondary faults located in the footwall of the main fault, which are interpreted as  $15\text{--}20^\circ$  SW dipping Riedel faults that entail bed back-rotation.



**Figure 9.** Mohr circle obtained from the undrained triaxial test results of three samples of sandy silts from the Santopétar outcrop.

Stages 2, 3 and 4 illustrate the formation of the hanging wall roll-over near a southwest dipping ramp as well as secondary fault development. Following this possible explanation, the hanging wall roll-over would have developed due to the existence of a ramp located to the northeast and now eroded away, so that no beds correlate between the hanging wall and the footwall. Therefore, we can only estimate a minimum extension of  $\sim 60$  m in view of the distance between the hanging wall antiform and the northeastern end of the outcrop. Stage 3 shows the restoration of the C1 syn-extensional bed. We can coherently flatten C1 top and base in the youngest restoration stage.

## 8. Discussion

[36] Here we provide examples of small and medium-scale ramp-flat-ramp and associated extensional shear zones developed in a mechanically layered sequence, active at a low confining pressure and therefore at very shallow depth. The studied faults feature small amounts of slip, making it possible to analyze fault nucleation, linkage, propagation, and associated folding. From a regional point of view, our results constrain the continuity of the lower Miocene extensional systems within the metamorphic complexes of the Eastern Betic Internal Zones, during the Serravallian-lower Tortonian, as well as their relationship with the intramontane basin formation.

### 8.1. Gravitational Versus Tectonic Origin

[37] Gravitational sliding of the uppermost sediment layers commonly occurs in deltaic environments toward the delta slope [Damuth, 1994; Maloney *et al.*, 2010]. The extensional backward thin-skinned structures that result from this gravitational process are quite similar to those found in the Huércal-Overa Basin. Landslides eventually reach the surface, producing compressive deformation in their fronts. However, no compressional structures were identified in connection to the normal faults described.

[38] Moreover, in order to discern between a gravitational or a tectonic origin of the studied structures, we reconstructed the delta slope direction and compared it with the

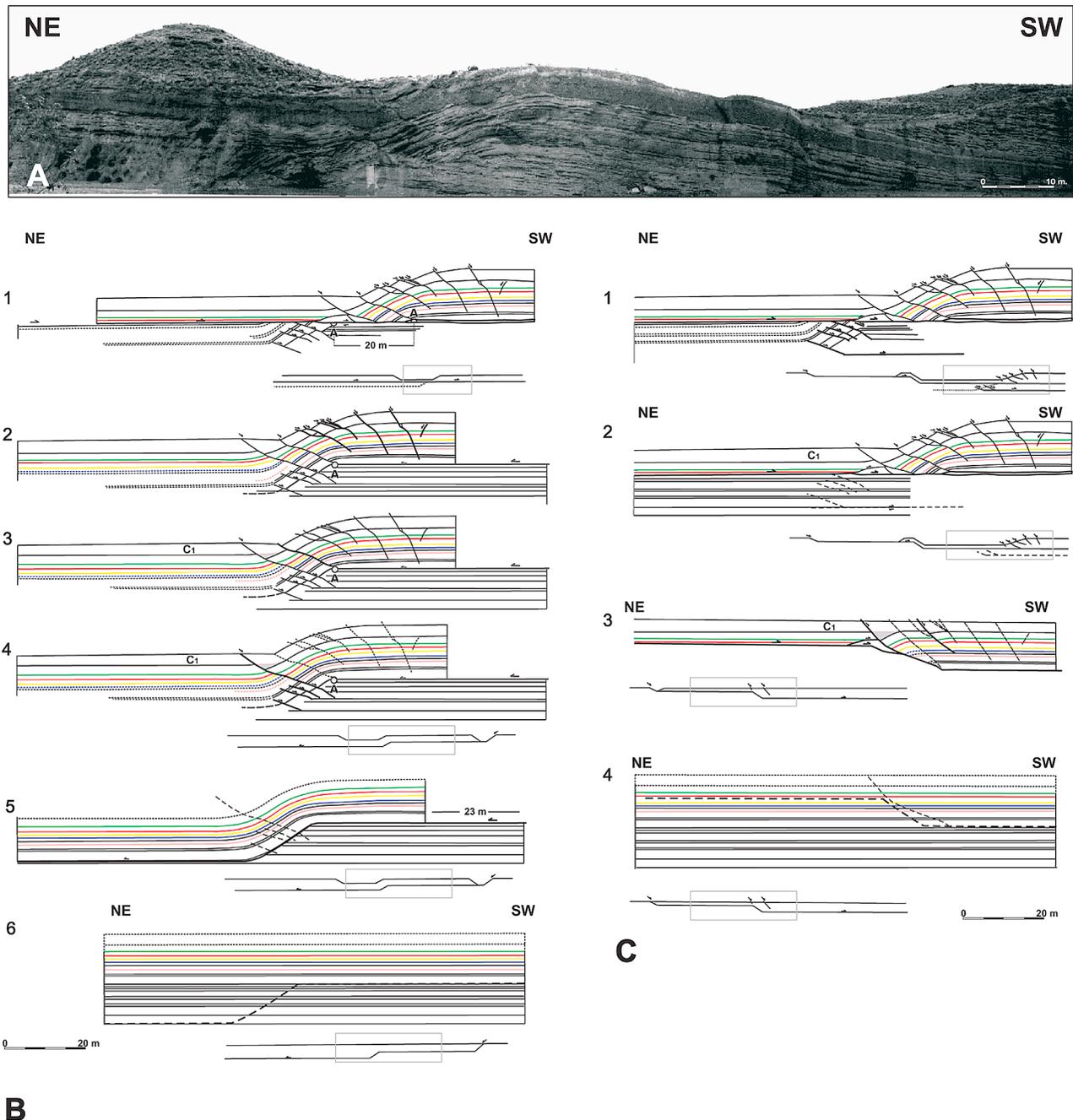
fault kinematic data obtained. Imbricate pebbles from the conglomeratic levels allowed us to accurately estimate the flow direction that presumably coincided with the paleoslope direction. The paleocurrent indicators from the continental red conglomerate formation and the conglomerate levels of the fluvial-deltaic studied unit, though scattered, are predominantly directed toward the E and N [Montenat *et al.*, 1990; Meijninger, 2006; Pedrera *et al.*, 2007].

[39] Figure 11 shows that the N to E paleoslope direction does not coincide with the top-to-the-SW to -SSW kinematics of the studied LANFs. This direction of movement also matches the NNE-SSW extension deduced from kinematic analysis of the HANFs. Therefore, the observed extensional detachments and duplexes have an unambiguously tectonic origin.

### 8.2. Near-Surface Ramp-Flat-Ramp Normal Fault Evolution: Fault Linkage and Propagation

[40] HANFs sometimes crosscut along all a fluvial-deltaic sequence, but more often they localize their slip in sandy silt beds. Failure analysis of the sandy silts of our study, performed after triaxial testing, gave a low cohesive strength ( $C_0 = 7$  kPa,  $\mu = 34^\circ$ ), which is consistent with a straightforward reactivation of bedding as LANFs. The two observed structures derived from the linkage between HANFs and LANFs are extensional ramp-flat-ramp and duplex fault zones.

[41] Shearing along bedding reactivated as LANFs favors the formation of Riedel faults, especially in the releasing overstep sectors between two nearly parallel flat fault segments. Progressive linkage of Riedel faults with the main detachment faults produces horsetail structures. An extensional duplex involves a set of imbricate faults—in our case Riedel faults—that transfer the displacement between parallel detachments. Horses are back-rotated and transported within the fault system. The term “extensional duplex” was established by Gibbs [1984] to describe the structural style characterized by connected extensional fault segments limiting rock lenses (horses) commonly associated with ramp-flat-ramp normal faults, equivalent to the duplexes defined



**Figure 10.** (a) Santopétar ramp-flat-ramp extensional fault and (b and c) possible restorations.

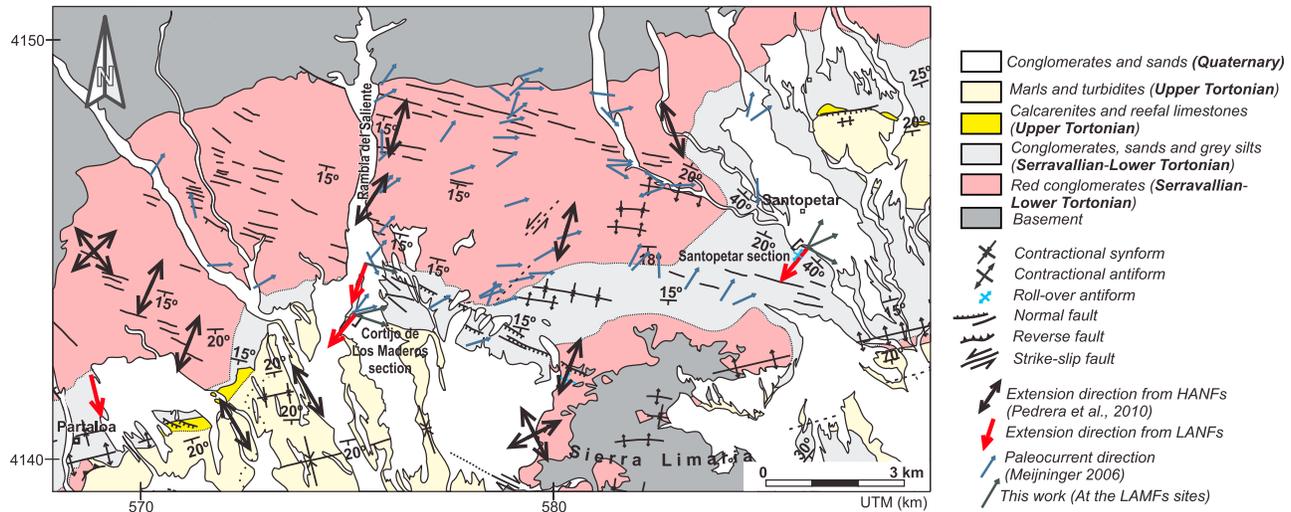
in contractional and strike-slip faults [Boyer and Elliott, 1982; Woodcock and Fischer, 1986]. Despite the vast literature describing the styles of extensional faulting, natural examples of ramp-flat-ramp normal faults and extensional duplexes are very scarce [Root, 1990; Benedicto *et al.*, 1999; Gabrielsen and Clausen, 2001; Vetti and Fossen, 2012]. In the Betic Cordillera, several examples have been described in basement metamorphic rocks developed in deeper parts of the crust and latterly exhumed [e.g., Martínez-Martínez *et al.*, 2002].

[42] All the extensional duplex examples documented in the Huércal-Overa Basin are formed by parallel LANFs

linked by means of Riedel faults. Thus, the connection between extensional flat fault segments and subsidiary Riedel faults is recognized as a mechanism that could derive into the growth of extensional or individual horses, just as Woodcock and Fischer [1986] described in the context of strike-slip faults.

### 8.3. On Extensional Fault-Related Folding

[43] Field and modeling studies of extensional fault-related folds illustrate the variety of fold styles and folding mechanisms [Schlische, 1993; Janecke *et al.*, 1998; Keller and Lynch, 1999; Varga *et al.*, 2004; White and Crider,



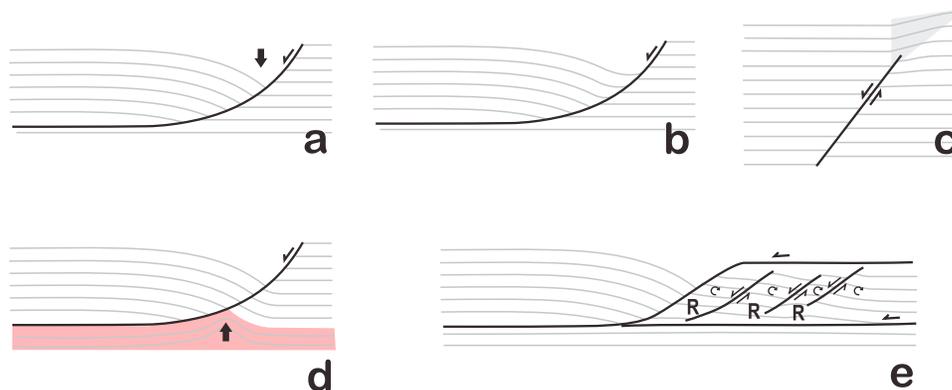
**Figure 11.** Simplified geological map of the northern part of the Huércal-Overa Basin marking the extension direction obtained from high-angle microfaults analysis [Pedrera et al., 2010], the extension direction deduced from the kinematics indicators in low-angle normal faults, and the paleocurrent direction deduced from imbricate pebbles [Meijninger, 2006] marking the paleoslope during the Serravallian-early Tortonian.

2006; Ford et al., 2007]. According to Janecke et al. [1998], the main mechanisms of extensional folding are fault-bend folding above fault-parallel (roll-over, Figure 12a) and fault-perpendicular bends, displacement gradients along normal faults, fault-drag (Figure 12b), fault-propagation folds (Figure 12c), isostatic adjustments, and compound folds.

[44] Another mechanism evoked to explain extensional folding involves the plasticity of underlying rocks that expand upwards due to unload linked to normal faulting [Koyi and Skelton, 2001]. During normal faulting the footwall slightly flexes upward to gravitationally re-equilibrate with the unloaded hangingwall (Figure 12d). Nucleation of the footwall folds occurs in the area where the high-dipping normal fault reaches the underlying viscous layer, parallelizing and decreasing their dip. This folding mechanism is quite similar to the one responsible for the development of salt rollers as described by Brun and Mauduit [2009].

[45] The meso-scale examples studied in the Huércal-Overa Basin illustrate that back-rotation between discrete Riedel faults provides an additional mechanism of extensional folding of subhorizontal layers. Riedel faults, which are frequently associated with releasing overstep zones between parallel detachments, produce the progressive block rotation. As a result, the beds curve upward, developing gentle synforms (Figure 12e). This mechanism is equivalent to that described by Boudon et al. [1976] for strike-slip faults and more recently by Harris [2003] in high-grade metamorphic rocks.

[46] Considering the unequivocal extensional kinematics of the main flat fault fitting with the kinematics of the secondary faults, the absence of reverse faults in the outcrop, and the restoration of the syn-extensional C1 level, we interpret the Santopétar structure as most likely associated with a single top-to-the-southwest extension accommodated



**Figure 12.** Mechanisms of extensional folding: (a) fault-bend folding, (b) fault-drag, (c) fault-propagation fold, (d) footwall flexure upward to gravitationally re-equilibrate with the unloaded hangingwall during normal faulting, and (e) back-rotation between discrete Riedel faults.

along a ramp-flat-ramp surface. During the displacement of the hanging wall above the flat fault segment, the synform developed in the footwall linked to the back-rotation of the blocks bounded by SW-dipping Riedel normal faults. During the displacement of the hanging wall above the flat fault segment, the synform developed in the footwall linked to the back-rotation of the blocks bounded by SW-dipping Riedel normal faults.

#### 8.4. Regional Implications

[47] Augier *et al.* [2005b] propose that subsidence of the sedimentary basin during the deposition of the studied Serravallian-lower Tortonian unit is coeval with the last exhumation of the Nevado-Filabride Complex below the regional Filabres extensional shear zone. However, the Alpujarride/Nevado-Filabride contact, with a presumably extensional west-directed character, does not crop out in the Limaria sector, instead being covered by the Serravallian-lower Tortonian red conglomerates (Figure 3). In addition, the top-to-the-N detachments developed within Alpujarride units, the Variegato/Almanzora thrust and the Almagro detachment, clearly took place before the Serravallian-lower Tortonian.

[48] Therefore, the detachments affecting the basement rocks in this part of the Betic Cordillera were active prior to the basin formation, meaning they are unconnected with the studied near-surface ramp-flat-ramp normal faults that crosscut the Serravallian-early Tortonian sedimentary unit of the Huércal-Overa Basin. This scenario is also consistent with the kinematic divergence between the N transport direction of the Alpujarride detachments, the W-directed Alpujarride/Nevado-Filabride extensional contact, and the SSW late extension.

#### 9. Conclusions

[49] The growth of LANFs in the brittle/ductile multilayer sequence of the Huércal-Overa Basin (SE Spain) is characterized here on the basis of structural data. Faulting processes occurred during sedimentation, at low confining pressures. The estimated maximum thickness of the fluvial-deltaic sedimentary formation is 300 m, and the syn-sedimentary features reveal very shallow development. Sandy silts beds with a low cohesive strength ( $C_0 = 7$  kPa,  $\mu = 34^\circ$ ) are reactivated as LANFs. A tectonic origin is supported instead of the possible gravitational origin after reconstruction of the paleoslope direction from the imbricate pebbles and comparison of the senses of movement deduced from fault slicken-lines.

[50] HANFs nucleated in the weak conglomerate levels would have started as shear joints. After deformation reached up to the sandy silts, it progressed along the bed, sometimes favoring the linkage between HANFs developed at different levels in the layered sequence and producing the ramp-flat-ramp geometry. Extensional duplexes produced after the linkage of horizontal parallel-bedding extensional faults through Riedel faults. In addition to roll-overs developed in the hanging wall of ramp-flat-ramp normal faults, synforms linked to these extensional duplexes are illustrated. In short, the back-rotation between normal Riedel faults provides a mechanism of extensional folding of subhorizontal layers.

[51] The Serravallian-early Tortonian clastic deposits represent the end of the main rifting event recorded in the Alboran Domain, which culminated with the Alboran Basin formation in Burdigalian-Langhian times. This continental/shallow marine sedimentary unit seals the Filabres extensional shear zone in the Huércal-Overa Basin, postdating its activity and the extensional exhumation of the Nevado-Filabride Complex in the eastern Betics.

[52] The presence of near-surface LANFs in the sedimentary rocks of the Huércal-Overa Basin does not imply their connection with either the outcropping Alpujarride detachment or the Alpujarride/Nevado-Filabride extensional shear zone. These detachments are clearly sealed by the Serravallian-lower Tortonian sediments that fill in the Huércal-Overa Basin, and their kinematics are unable to coexist with the faults affecting the basin sediments. The studied LANFs are influenced by the rock anisotropy of a specific sedimentary unit where sandy silts alternate with very peculiar elastic properties. These faults belong to an extensional system together with widespread high-angle normal faults formed under NE-SW to NNE-SSW extension. They accommodate moderate extension rather than belonging to a large crustal extensional system connected with a regional detachment at depth. The link between this extensional system and the regional detachment within metamorphic complexes would be subjected only to local reactivations that have not yet been documented in the studied area.

[53] **Acknowledgments.** This study was supported by the projects CSD2006-00041, CGL-2008-03474-E, CGL2010-21048, and CGL 2008 0367 E/BTE of the Spanish Ministry of Science and Education, as well as by Research Group RNM-148 and RNM-5388 of the Junta de Andalucía Regional Government. We acknowledge the remarks made by Romain Augier, Whitney Behr, and Juan Carlos Balanyá that noticeably improved the manuscript. Jean Sanders revised the English manuscript style.

#### References

- Abers, G. A. (2009), Slip on shallow-dipping normal faults, *Geology*, 37(8), 767–768, doi:10.1130/focus082009.1.
- Agard, P., R. Augier, and P. Monié (2011), Shear band formation and strain localization on a regional scale: Evidence from anisotropic rocks below a major detachment (Betic Cordilleras, Spain), *J. Struct. Geol.*, 33, 114–131, doi:10.1016/j.jsg.2010.11.011.
- Anderson, E. M. (1951), *The Dynamics of Faulting*, 206 pp., Oliver and Boyd, Edinburgh, U. K.
- Augier, R. (2004), Evolution tardi-orogénique des Cordilières Bétiques (Espagne): Apports d'un étude intégrée, PhD thesis, Univ. de Pierre et Marie Curie, Paris.
- Augier, R., P. Agard, P. Monié, L. Jolivet, C. Robin, and G. Booth-Rea (2005a), Exhumation, doming and slab retreat in the Betic Cordillera (SE Spain): In situ 40Ar/39Ar ages and P–T–d–t paths for the Nevado-Filabride complex, *J. Metamorph. Geol.*, 23, 357–381, doi:10.1111/j.1525-1314.2005.00581.x.
- Augier, R., L. Jolivet, and C. Robin (2005b), Late Orogenic doming in the eastern Betic Cordilleras: Final exhumation of the Nevado-Filabride complex and its relation to basin genesis, *Tectonics*, 24, TC4003, doi:10.1029/2004TC001687.
- Axen, G. J. (1988), The geometry of planar domino style normal faults above a dipping basal detachment, *J. Struct. Geol.*, 10, 405–411, doi:10.1016/0191-8141(88)90018-1.
- Axen, G. J. (1992), Pore pressure, stress increase, and fault weakening in low-angle normal faulting, *J. Geophys. Res.*, 97, 8979–8991, doi:10.1029/92JB00517.
- Axen, G. J. (1999), Low-angle normal fault earthquakes and triggering, *Geophys. Res. Lett.*, 26, 3693–3696, doi:10.1029/1999GL005405.
- Balanyá, J. C., and V. García-Dueñas (1987), Les directions structurales dans le Domaine d'Alborán de part et d'autre du Détroit de Gibraltar, *C. R. Acad. des Sci., Ser. II*, 304, 929–932.

- Balanyá, J. C., V. García-Dueñas, J. M. Azañón, and M. Sánchez-Gómez (1997), Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics, Gibraltar Arc), *Tectonics*, *16*, 226–238, doi:10.1029/96TC03871.
- Balanyá, J. C., V. García-Dueñas, J. M. Azañón, and M. Sánchez-Gómez (1998), Reply to comment by J. P. Platt on “Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics, Gibraltar Arc),” *Tectonics*, *17*, 977–981, doi:10.1029/1998TC900006.
- Bally, A. W., D. Bernoulli, G. A. Davis, and L. Montardet (1981), Listric normal faults, *Oceanol. Acta*, *4*, 87–101.
- Bardet, J. P. (1997), *Experimental Soil Mechanics*, Prentice Hall, Upper Saddle River, N. J.
- Barragán, G. (1997), Evolución geodinámica de la Depresión de Vera, PhD thesis, Univ. of Granada, Granada, Spain.
- Benedicto, A., M. Séguret, and P. Labaume (1999), Interaction between faulting, drainage and sedimentation in extensional hanging-wall syncline basins: Example of the Oligocene Matelles Basin (Gulf of Lion rifted margin, SE France), in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, edited by B. Durand et al., *Geol. Soc. Spec. Publ.*, *156*, 81–108.
- Blumenthal, M. (1927), Versuch einer tektonischen Gliederung der Betsischen Kordilleren von Central und Südwest Andalusien, *Eclogae Geol. Helv.*, *20*, 487–592.
- Booth-Rea, G., J. M. Azañón, B. Goffé, O. Vidal, and J. M. Martínez-Martínez (2002), High-pressure, low-temperature metamorphism in the Alpujarride units outcropping in southeastern Betics (Spain), *C. R. Geosci.*, *334*, 857–865, doi:10.1016/S1631-0713(02)01787-X.
- Booth-Rea, G., J. M. Azañón, J. M. Martínez-Martínez, O. Vidal, and V. García-Dueñas (2003), Análisis estructural y evolución tectonometamórfica del basamento de las cuencas neógenas de Vera y Huércal-Overa, Béticas orientales, *Rev. Soc. Geol. Esp.*, *16*(3–4), 193–211.
- Booth-Rea, G., J. M. Azañón, and V. García-Dueñas (2004), Extensional tectonics in the northeastern Betics (SE Spain): Case study of extension in a multilayered upper crust with contrasting rheologies, *J. Struct. Geol.*, *26*, 2039–2058, doi:10.1016/j.jsg.2004.04.005.
- Booth-Rea, G., J. M. Azañón, J. M. Martínez-Martínez, O. Vidal, and V. García-Dueñas (2005), Contrasting structural and P-T evolution of tectonic units in the southeastern Betics: Key for understanding the exhumation of the Alboran Domain HP/LT crustal rocks (western Mediterranean), *Tectonics*, *24*, TC2009, doi:10.1029/2004TC001640.
- Booth-Rea, G., C. Ranero, J. M. Martínez-Martínez, and I. Grevemeyer (2007), Crustal types and Tertiary tectonic evolution of the Alboran sea, western Mediterranean, *Geochim. Geophys. Geosyst.*, *8*, Q10005, doi:10.1029/2007GC001639.
- Boudon, J., J. F. Gamond, J. P. Gratier, J. P. Robert, J. P. Depardon, M. Gay, M. Ruhland, and P. Vialon (1976), L’arc alpin occidental: Réorientation de structures primitivement E-W par glissement et étirement dans un système de compression global N-S, *Eclogae Geol. Helv.*, *69*(2), 509–519.
- Boulton, C., T. Davies, and M. McSaveney (2009), The frictional strength of granular fault gouge: Application of theory to the mechanics of low-angle normal faults, *Geol. Soc. Lond. Spec. Publ.*, *321*, 9–31, doi:10.1144/SP321.2.
- Boyer, S., and D. Elliott (1982), Thrusts systems, *AAPG Bull.*, *66*, 1196–1230.
- Briand, M. (1981), *Evolution morpho-tectonique du bassin Néogène de Huércal Overa (Cordillères bétiques orientales, Espagne)*, *Doc. Trav. IGAL*, vol. 4, 208 pp., Inst. Géol. Albert de Lapparent, Paris.
- Brun, J. P., and T. P. O. Mauduit (2009), Salt rollers: Structure and kinematics from analogue modelling, *Mar. Pet. Geol.*, *26*, 249–258, doi:10.1016/j.marpetgeo.2008.02.002.
- Cichanski, M. (2000), Low-angle, range-flank faults in the Panamint, Inyo, and Slate ranges, California: Implications for recent tectonics of the Death Valley region, *Geol. Soc. Am. Bull.*, *112*, 871–883, doi:10.1130/0016-7606(2000)112<871:LRFITP>2.0.CO;2.
- Collettini, C., and M. R. Barchi (2002), A low angle normal fault in the Umbria region (Central Italy): A mechanical model for the related microseismicity, *Tectonophysics*, *359*, 97–115, doi:10.1016/S0040-1951(02)00441-9.
- Collettini, C., N. De Paola, and N. R. Gouly (2006), Switches in the minimum compressive stress direction induced by overpressure beneath a low-permeability fault zone, *Terra Nova*, *18*, 224–231, doi:10.1111/j.1365-3121.2006.00683.x.
- Comas, M. C., J. P. Platt, J. I. Soto, and A. B. Watts (1999), The origin and tectonic history of the Alborán Basin: Insights from Leg 161 Results, *Proc. Ocean Drill. Program, Sci. Results*, *161*, 555–580.
- Crespo-Blanc, A. (1995), Interference pattern of extensional fault systems: A case study of the Miocene rifting of the Alboran basement (north of Sierra Nevada, Betic chain), *J. Struct. Geol.*, *17*, 1559–1569, doi:10.1016/0191-8141(95)E0044-D.
- Crespo-Blanc, A., and J. Campos (2001), Structure and kinematics of the South Iberian paleomargin and its relationship with the Flysch Trough units: Extensional tectonics within the Gibraltar Arc fold-and-thrust belt (western Betics), *J. Struct. Geol.*, *23*, 1615–1630, doi:10.1016/S0191-8141(01)00012-8.
- Cuevas, J., F. Aldaya, F. Navarro-Vila, and J. M. Tubía (1986), Caractérisation de deux étapes de charriages principales dans les nappes Alpujarrides centrales (Cordillères Bétiques, Espagne), *C. R. Acad. Sci., Ser. II*, *302*, 1177–1180.
- Damuth, J. E. (1994), Neogene gravity tectonics and depositional processes on the deep Niger Delta continental margin, *Mar. Pet. Geol.*, *11*(3), 320–346, doi:10.1016/0264-8172(94)90053-1.
- De Jong, K. (1991), Tectono-metamorphic studies and radiometric dating in the Betic Cordilleras (SE Spain), PhD thesis, 204 pp., Vrije Univ., Amsterdam.
- Dewey, J. F., M. L. Helman, E. Turco, D. H. W. Hutton, and S. D. Knott (1989), Kinematics of the western Mediterranean, in *Alpine Tectonics*, edited by M. P. Coward, D. Dietrich, and R. G. Park, *Geol. Soc. Spec. Publ.*, *45*, 265–283.
- Egeler, C. G. (1963), On the tectonics of the eastern Betic Cordilleras (SE Spain), *Geol. Rundsch.*, *52*, 260–269.
- Faccenna, C., C. Piromallo, A. Crespo-Blanc, L. Jolivet, and F. Rossetti (2004), Lateral slab deformation and the origin of the western Mediterranean arcs, *Tectonics*, *23*, TC1012, doi:10.1029/2002TC001488.
- Ford, M., C. Le Carlier de Veslud, and O. Bourgeois (2007), Kinematic and geometric analysis of fault-related folds in a rift setting: The Dannemarie Basin, Upper Rhine Graben, France, *J. Struct. Geol.*, *29*, 1811–1830, doi:10.1016/j.jsg.2007.08.001.
- Gabrielsen, R. H., and J. A. Clausen (2001), Horses and duplexes in extensional regimes: A scale-modelling contribution, in *Tectonic Modelling: A Volume in Honor of Hans Ramberg*, edited by H. A. Koyi and N. S. Mancktelow, *Mem. Geol. Soc. Am.*, *193*, 207–220.
- Galindo-Zaldívar, J., F. González-Lodeiro, and A. Jabaloy (1989), Progressive extensional shear structures in a detachment contact in the western Sierra Nevada (Betic Cordilleras, Spain), *Geodin. Acta*, *3*, 73–85.
- García-Dueñas, V., and J. M. Martínez-Martínez (1988), Sobre el adelgazamiento Mioceno del dominio cortical de Alborán: El despegue extensional de Filábride, *Geogaceta*, *5*, 53–55.
- García-Dueñas, V., J. C. Balanyá, and J. M. Martínez-Martínez (1992), Miocene extensional detachments in the outcropping basement of the northern Alboran Basin (Betics) and their tectonic implications, *Geo Mar. Lett.*, *12*, 88–95, doi:10.1007/BF02084917.
- Gibbs, A. D. (1984), Structural evolution of extensional basin margins, *J. Geol. Soc. London*, *141*, 609–620.
- Gómez-Pugnaire, M. T., J. Galindo-Zaldívar, D. Rubatto, F. González-Lodeiro, V. López Sánchez-Vizcaíno, and A. Jabaloy (2004), A reinterpretation of the Nevado-Filábride and Alpujarride complex (Betic Cordillera): Field, petrography and U-Pb ages from orthogneisses western Sierra Nevada, S Spain, *Schweiz. Mineral. Petrogr. Mitt.*, *84*, 303–322.
- Guerra Merchán, A. (1992), Origen y relleno sedimentario de la cuenca neógena del Corredor del Almanzora y áreas limítrofes (Cordillera Bética), PhD thesis, Univ. de Granada, Granada, Spain.
- Harris, L. B. (2003), Folding in high-grade rocks due to back-rotation between shear zones, *J. Struct. Geol.*, *25*, 223–240, doi:10.1016/S0191-8141(02)00024-X.
- Head, K. H. (1998), *Manual of Soil Laboratory Testing*, vol. 3, *Effective Stress Tests*, 2nd ed., John Wiley, Hoboken, N. J.
- Jabaloy, A., J. Galindo-Zaldívar, and F. González-Lodeiro (1992), The Mecina extensional system: Its relation with the post-Aquitania piggy-back basins and the paleostresses evolution (Betic Cordilleras, Spain), *Geo Mar. Lett.*, *12*, 96–103, doi:10.1007/BF02084918.
- Jabaloy, A., J. Galindo-Zaldívar, and F. González-Lodeiro (1993a), The Alpujarride-Nevado-Filábride extensional shear zone, Betic Cordillera, SE Spain, *J. Struct. Geol.*, *15*(3–5), 555–569, doi:10.1016/0191-8141(93)90148-4.
- Jabaloy, A., J. Galindo-Zaldívar, A. Guerra-Merchán, and F. González-Lodeiro (1993b), Listric normal faults: Constraints to the geometric and kinematic analysis from the study of natural examples, *Doc. BRGM*, *219*, 100–101.
- Jabaloy-Sánchez, A., E. M. Fernández-Fernández, and F. González-Lodeiro (2007), A cross section of the eastern Betic Cordillera (SE Spain) according field data and a seismic reflection profile, *Tectonophysics*, *433*, 97–126, doi:10.1016/j.tecto.2006.11.004.
- Janecke, S. U., C. J. Vandenberg, and J. J. Blankenau (1998), Geometry, mechanism, and significance of extensional folds from examples in the Rock Mountain Basin and Range Province, U.S.A., *J. Struct. Geol.*, *20*, 841–856, doi:10.1016/S0191-8141(98)00016-9.

- Jolivet, L., and C. Faccenna (2000), Mediterranean extension and the Africa-Eurasia collision, *Tectonics*, *19*, 1095–1109, doi:10.1029/2000TC900018.
- Keller, J. V. A., and G. Lynch (1999), Displacement transfer and forced folding in the Maritimes Basin of Nova Scotia, eastern Canada, *Geol. Soc. Spec. Publ.*, *169*, 87–101, doi:10.1144/GSL.SP.2000.169.01.07.
- Koyi, H., and A. D. L. Skelton (2001), Initiation of detachment faults: Insights from centrifuge modeling, *J. Struct. Geol.*, *23*, 1179–1185.
- Lister, G. S., and G. A. Davis (1989), The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, USA, *J. Struct. Geol.*, *11*, 65–94, doi:10.1016/0191-8141(89)90036-9.
- Loneragan, L., and N. White (1997), Origin of the Betic-Rif mountain belt, *Tectonics*, *16*, 504–522, doi:10.1029/96TC03937.
- López Sánchez-Vizcaíno, V., D. Rubatto, M. T. Gómez-Pugnaire, V. Trommsdorff, and O. Müntener (2001), Middle Miocene high-pressure metamorphism and fast exhumation of the Nevado-Filábride Complex, SE Spain, *Terra Nova*, *13*, 327–332, doi:10.1046/j.1365-3121.2001.00354.x.
- Luján, M., F. Storti, J. C. Balanyá, A. Crespo-Blanc, and F. Rossetti (2003), Role of decollement material with different rheological properties in the structure of the Aljibe thrust imbricate (Flysch Trough, Gibraltar Arc): An analogue modeling approach, *J. Struct. Geol.*, *25*, 867–881, doi:10.1016/S0191-8141(02)00087-1.
- Maloney, D., R. Davies, J. Imber, S. Higgins, and S. King (2010), New insights into deformation mechanisms in the gravitationally driven Niger Delta deep-water fold and thrust belt, *AAPG Bull.*, *94*(9), 1401–1424, doi:10.1306/01051009080.
- Martí, A., P. Queralt, E. Roca, J. Ledo, and J. Galindo-Zaldívar (2009), Geodynamic implications for the formation of the Betic-Rif orogen from magnetotelluric studies, *J. Geophys. Res.*, *114*, B01103, doi:10.1029/2007JB005564.
- Martín-Algarra, A. (1987), Evolución geológica alpina del contacto entre las zonas internas y externas de la Cordillera Bética, PhD thesis, Univ. of Granada, Granada, Spain.
- Martínez-Martínez, J. M., and J. M. Azañón (1997), Mode of extensional tectonics in the southeastern Betics (SE Spain): Implications for the tectonic evolution of the peri-Alborán orogenic system, *Tectonics*, *16*, 205–225, doi:10.1029/97TC00157.
- Martínez-Martínez, J. M., J. I. Soto, and J. C. Balanyá (2002), Orthogonal folding of extensional detachments: Structure and origin of the Sierra Nevada elongated dome (Betics, SE Spain), *Tectonics*, *21*(3), 1012, doi:10.1029/2001TC001283.
- Martínez-Martínez, J. M., J. I. Soto, and J. C. Balanyá (2004), Elongated domes in extended orogens: A mode of mountain uplift in the Betics (southeast Spain), in *Gneiss Domes in Orogeny*, edited by D. L. Whitney, C. Teyssier, and C. S. Siddoway, *Spec. Pap. Geol. Soc. Am.*, *380*, 243–266.
- Mazzoli, S., and M. Helman (1994), Neogene patterns of relative plate motion for Africa-Europe: Some implications for recent central Mediterranean tectonics, *Geol. Rundsch.*, *83*, 464–468.
- Meijninger, B. M. L. (2006), Late-orogenic extension and strike-slip deformation in the Neogene of southeastern Spain. PhD thesis, Geol. Ultralect., Univ. Utrecht, Utrecht, Netherlands.
- Monié, P., J. Galindo-Zaldívar, F. González-Lodeiro, B. Goffé, and A. Jabaloy (1991), <sup>40</sup>Ar/<sup>39</sup>Ar geochronology of Alpine tectonism in the Betic Cordilleras (southern Spain), *J. Geol. Soc.*, *148*, 289–297, doi:10.1144/gsjgs.148.2.0289.
- Montenat, C., and P. Ott d'Estevou (1990), Eastern Betic Neogene basins: A review, in *Les Bassins Néogènes du Domaine Bétique Orientale (Espagne)*, *Doc. Trav. IGAL*, vol. 12–13, edited by C. Montenat, pp. 9–15, Inst. Géol. Albert de Lapparent, Paris.
- Montenat, C., P. Ott d'Estevou, and G. Chapelle de la (1990), Les series Neogenes entre Lorca et Huércal-Overa, in *Les Bassins Néogènes du Domaine Bétique Oriental (Espagne)*, *Doc. Trav. IGAL*, vol. 12–13, pp. 281–286, Inst. Géol. Albert de Lapparent, Paris.
- Mora, M. (1993), Tectonic and sedimentary analysis of the Huércal-Overa region, SE Spain, Betic Cordillera, PhD thesis, Oxford Univ., Oxford, U. K.
- Morley, C. K. (1999), Marked along strike variations in dip of normal faults, the Lorchar fault, N Kenya: A possible cause for the metamorphic core complexes, *J. Struct. Geol.*, *21*, 479–492, doi:10.1016/S0191-8141(99)00043-7.
- Orozco, M., A. M. Álvarez-Valero, F. M. Alonso-Chaves, and J. P. Platt (2004), Internal structure of a collapsed terrain. The Lu'jar syncline and its significance for the fold- and sheet-structure of the Alborán Domain (Betic Cordilleras, Spain), *Tectonophysics*, *385*, 85–104.
- Peacock, D. C. P., and D. J. Sanderson (1992), Effects of layering and anisotropy on fault geometry, *J. Geol. Soc.*, *149*, 793–802, doi:10.1144/gsjgs.149.5.0793.
- Pedrera, A., J. Galindo-Zaldívar, C. Sanz de Galdeano, and A. C. López-Garrido (2007), Fold and fault interactions during the development of an elongated narrow basin: The Almanzora Neogene-Quaternary Corridor (SE Betic Cordillera, Spain), *Tectonics*, *26*, TC6002, doi:10.1029/2007TC002138.
- Pedrera, A., J. Galindo-Zaldívar, A. Ruiz-Constan, C. Duque, C. Marín-Lechado, and I. Serrano (2009), Recent large fold nucleation in the upper crust: Insight from gravity, magnetic, magnetotelluric and seismicity data (Sierra de Los Filabres-Sierra de Las Estancias, Internal Zones, Betic Cordillera), *Tectonophysics*, *463*, 145–160, doi:10.1016/j.tecto.2008.09.037.
- Pedrera, A., J. Galindo-Zaldívar, A. Tello, and C. Marín-Lechado (2010), Intramontane basin development related to contractional and extensional structure interaction at the termination of a major sinistral fault: The Huércal-Overa Basin (eastern Betic Cordillera), *J. Geodyn.*, *49*, 271–286, doi:10.1016/j.jog.2010.01.008.
- Platt, J. P. (1998), Comment on “Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betic, Gibraltar Arc)” by J. C. Balanyá et al., *Tectonics*, *17*, 973–976, doi:10.1029/1998TC900005.
- Platt, J. P., and R. L. M. Vissers (1989), Extensional collapse of thickened continental lithosphere: A working hypothesis for the Alboran Sea and Gibraltar Arc, *Geology*, *17*, 540–543, doi:10.1130/0091-7613(1989)017<0540:ECOTCL>2.3.CO;2.
- Platt, J. P., S. P. Kelley, A. Carter, and M. Orozco (2005), Timing of tectonic events in the Alpujarride Complex, Betic Cordillera, southern Spain, *J. Geol. Soc.*, *162*(1–12), 451–462, doi:10.1144/0016-764903-039.
- Platt, J. P., R. Anczkiewicz, J. I. Soto, S. P. Kelley, and M. Thirlwall (2006), Early Miocene continental subduction and rapid exhumation in the western Mediterranean, *Geology*, *34*, 981–984, doi:10.1130/G22801A.1.
- Puga, E., J. M. Nieto, A. Díaz de Federico, J. L. Bodinier, and L. Morten (1999), Petrology and Metamorphic evolution of ultramafic rocks and dolerite dykes of the Betic Ophiolitic Association (Mulhacén Complex, SE Spain): Evidence of eo-Alpine subduction following an ocean-floor metamorphic process, *Lithos*, *49*, 23–56, doi:10.1016/S0024-4937(99)00035-3.
- Root, K. G. (1990), Extensional duplex in the Purcell Mountains of southeastern British Columbia, *Geology*, *18*(5), 419–421, doi:10.1130/0091-7613(1990)018<0419:EDITPM>2.3.CO;2.
- Rosenbaum, G., G. S. Lister, and C. Duboz (2002), Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene, *J. Virtual Explorer*, *8*, 107–126.
- Sanz de Galdeano, C., and F. García-Tortosa (2002), Alpujarride attribution of the supposed “Almagrider complex” (Betic Internal Zone, Almería Province, Spain), *C. R. Geosci.*, *334*, 355–362, doi:10.1016/S1631-0713(02)01752-2.
- Sanz de Galdeano, C., and J. A. Vera (1992), Stratigraphic record and palaeogeographical context of the Neogene basins in the Betic Cordillera, Spain, *Basin Res.*, *4*, 21–36, doi:10.1111/j.1365-2117.1992.tb00040.x.
- Schlische, R. W. (1993), Anatomy and evolution of the Triassic-Jurassic continental rift system, eastern North America, *Tectonics*, *12*, 1026–1042, doi:10.1029/93TC01062.
- Shelton, J. W. (1984), Listric normal faults: An illustrated summary, *AAPG Bull.*, *68*, 801–815.
- Simancas, J. F., and J. Campos (1993), Compresión NNW-SSE tardi a post-metamórfica y extensión subordinada en el Complejo Alpujarride (Dominio de Alborán, Orogénico Bético), *Rev. Soc. Geol. Esp.*, *6*, 23–35.
- Simon, O. J. (1963), Geological investigations in the Sierra de Almagro, southeastern Spain, PhD thesis, 164 pp., Univ. of Amsterdam, Amsterdam.
- Smith, S. A. F., and D. R. Faulkner (2010), Laboratory measurements of the frictional properties of the Zuccale low-angle normal fault, Elba Island, Italy, *J. Geophys. Res.*, *115*, B02407, doi:10.1029/2008JB006274.
- Sorel, D. (2000), A Pleistocene and still-active detachment fault and the origin of the Corinth-Patras rift, Greece, *Geology*, *28*, 83–86, doi:10.1130/0091-7613(2000)28<83:APASDF>2.0.CO;2.
- Tubía, J. M., and J. I. Gil Ibarra (1991), Eclogites of the Ojén nappe: A record of subduction in the Alpujarride complex (Betic Cordilleras, southern Spain), *J. Geol. Soc.*, *148*, 801–804, doi:10.1144/gsjgs.148.5.0801.
- Van Bemmelen, R. W. (1927), Bijdrage tot de geologie der Betisch Ketens in de provincie Granada, PhD thesis, 176 pp., Univ. of Delft, Delft, Netherlands.
- Varga, R. J., J. E. Faulds, L. W. Snee, S. S. Harlan, and L. Bettison-Varga (2004), Miocene extension and extensional folding in an anticlinal segment of the Black Mountains accommodation zone, Colorado River extensional corridor, southwestern United States, *Tectonics*, *23*, TC1019, doi:10.1029/2002TC001454.

- Vetti, V. V., and H. Fossen (2012), Origin of contrasting Devonian supra-detachment basin types in the Scandinavian Caledonides, *Geology*, *40*, 571–574, doi:10.1130/G32512.1.
- Weijermars, R., T. B. Roep, B. Van den Eeckhout, G. Postma, and K. Kleverlaan (1985), Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almería, Sorbas and Tabernas Basins of the Betic Cordilleras, SE Spain), *Geol. Mijnbouw*, *64*, 397–411.
- White, I. R., and J. G. Crider (2006), Extensional fault-propagation folds: Mechanical models and observations from the Modoc Plateau, northeastern California, *J. Struct. Geol.*, *28*, 1352–1370, doi:10.1016/j.jsg.2006.03.028.
- Woodcock, N. H., and M. Fischer (1986), Strike-slip duplexes, *J. Struct. Geol.*, *8*, 725–735, doi:10.1016/0191-8141(86)90021-0.